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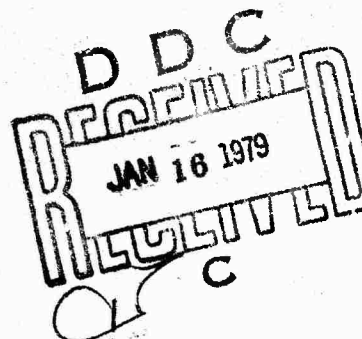
RADC-TR-78-222  
Final Technical Report  
October 1978



LARGE FORMAT MENSURATION STATION

Donald J. McCarthy  
Woodrow L. Hayes  
Alex R. Shevekov

Dest Data Corporation



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cision mensuration stages. Stereo mensuration is performed using a Master Stage/Slave Stage concept. The Master Stage is manually positioned by the operator and the Slave Stage is positioned relative to the Master with servo drive systems (X and Y axis). The operator maintains the parallax free model locally by adjusting X and Y parallax controls for the Slave Stage.

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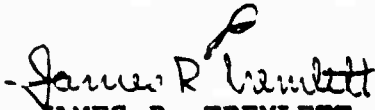
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## EVALUATION

The Foreign Technology Division (FTD) presently has at its disposal nine dual stage coordinate reading systems upon which they perform the majority of their stereo mensuration tasks. The most recent addition to their hardware inventory is the Large Format Dual Stereo Mensuration Station (LFDSMS) developed and delivered under this program. The LFDSMS has several unique features which separate it from its predecessors. The improved accuracy and larger mensuration stages are the most obvious and most important. These improvements address changing exploitation requirements dictated by new collection system technology. The device was configured to provide sub-micron measurement accuracy and improved production capacity with the flexibility to accommodate larger format input imagery. The system is utilized by intelligence analyst to derive extremely accurate photo coordinates from imagery inputs. RADC Technical Program Objective R1A, "Technical Intelligence", may be referenced for a more detailed description of the LFDSMS's import to the intelligence information collection environment.

  
JAMES R. TREMLETT  
Project Engineer



## SUMMARY

Dest Data Corporation received a task to design, build, and test a Large Format Dual Stereo Mensuration Station (LFDSMS) that is used to extract three-dimensional data from stereo film chips. To provide stereo mensuration capability over a 200 mm by 300 mm area and fulfill the overall dimensional restraints, it was necessary to design a system that differed from the previously designed Dual Stereo Mensuration Station (DSMS) that has been used for several years at the Foreign Technology Division of Wright-Patterson Air Force Base. The LFDSMS, like the DSMS, interfaces with a modified IBM 2740 communications terminal on line to an IBM 360/40 computer system; it utilizes a similar binocular microscope viewing system and is operated by nearly identical stage motion controls. The left, or master, stage (viewed by the operator's left eye) is manually positioned to points of interest. The right, or slave, stage (viewed by the operator's right eye) is servo controlled to track the motion of the master stage with a deviation not exceeding 0.2 microns. The coordinate position of the two stages is derived from a plane mirror interferometric metering system that has a least count of 0.1 microns and an accuracy of + or - 0.2 microns or one part in 40,000, or whichever is greater. Position read-out to the IBM 2740 is accomplished by the operator actuating a switch without the necessity of removing his hands from the stage motion controls. The slave stage can be servo-motor driven by means of a small "joystick" at seven different velocities from 5 microns per second to 1.5 mm per second, while the operator is observing imagery.

On the same control panel with the "joystick" are separate controls for adjusting the intensity of illumination of each stage, toggle valves for locking or unlocking the two stages, servo on-off switches, metering system reset switches, and a parallax reset switch.

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## SECTION I

### INTRODUCTION

The technical objective of Contract Number F30602-76-C-0279 was to design, build, and test a Large Format Dual Stereo Mensuration Station (LFDSMS) for extracting three-dimensional data from stereo film chips with accuracy exceeding the existing Micron Mensuration Stage. Data is read out to a modified IBM 2740 communications terminal on line to an IBM 360/40 computer system.

The LFDSMS consists of two units: (1) a console assembly consisting of an elevating table, support structure with control panel, two Mensuration Stages, and a binocular optical system attached to the two stages, and (2) a pneumatics/electronics assembly contained in a two-bay electronics cabinet.

A continuous comparison of the digital position of master and slave stages provides a drive signal to the slave stage servo motors. The slave stage position is maintained within 0.2 micron of the master stage position, plus or minus the inserted parallax number. The photo analyst, while viewing the stereo image, can continuously insert with a "joystick" a plus or minus parallax number in increments from 5.0 micron per second to 1.5 millimeters per second.

The master and slave stage images are combined in a binocular eyepiece such that the left eye views the master stage and the right eye views the slave stage. Microscopes, constructed with four objective lenses in a turret and focus capability, are mounted to each stage, forming an image of the film under study on its respective reticle, thereby providing a fixed reference on each stage. The images from the reticle are relayed to the eyepieces. The eyepiece/objective combinations give a magnification range from 17.5X to 250X.

This report contains detail descriptions of the LFDSMS development by individual parameter and subsystem. The following descriptions are presented: the electronics systems involved in the digital comparator, parallax accumulator and servo control; the interferometer metering system; the binocular viewing optical system; the mechanical system; and the pneumatic system.

The discussion covers development of the system including the results of the mock-up reviews with the customer. Added to this are the results of the acceptance tests conducted at Wright-Patterson AFB (FTD). Then, the conclusions reached from the development of the LFDSMS and the recommendations to be considered in the manufacture of future systems are presented.

## SECTION II

### ELECTRONIC SYSTEM

#### a. General Description of the Electronics of LFDSMS

The LFDSMS electronics utilizes the design concept of the DSMS including a majority of its electronic subassembly components. The major differences of the LFDSMS system are as follows:

- 1 - Master and slave stage incremental position changes acquired from serial data information from laser interferometer comparison circuitry.
- 2 - Absolute positional information of the master and slave stage is obtained via "Zero Reset" switches as actuated by the operator when a fixed mechanical reference point is ascertained.
- 3 - Capacity of the Arithmetic Unit increased to handle an X & Y displacement of the master and slave stages over a range of seven decimal digits.
- 4 - Redesign of the IBM 2740 typewriter control circuitry to handle the new seven digit format.
- 5 - Test display data storage capacity increased to seven digits.

#### b. Absolute Stage Position Detection and Processing

TTL 54193 type up/down counters are utilized for storing and incrementing the absolute position of each stage in their respective X & Y axes. The incremental position changes are derived from up/down direction and 0.1  $\mu$ m displacement pulse signals from the Laser Interferometer system. The absolute position of each stage is preset by the operator by clearing the up/down counters (actuating the "Zero Reset" switch) once a fixed mechanical reference point is encountered on the measurement stages.

The stored values in the up/down counters, four sets of seven BCD digit values for each of the two linear axes of the master and slave stages, are transferred in parallel form to the appropriate Arithmetic Unit stages, absolute position LED display indicators, and the Typewriter interface circuitry.

The Arithmetic Unit continuously processes the absolute position data information for Delta and Error servo drive signals at the same rate (3 KHz) and same format as in the DSMS

system, except for the following:

- 1 - D/A converter range for servo motor control is increased to a range of  $\pm 399.9 \mu\text{m}$ .
- 2 - Servo will slew if the error between the master and slave stage is  $>399.9 \mu\text{m}$ .
- 3 - For parallax insertion, variable stage speeds are one-half the DSMS values.

The master X & Y and slave X & Y absolute position LED display is continuously updated at a rate of 3 KHz.

The typewriter control circuitry acquires its print absolute data position only once and as soon as the "Read Out" switch is pressed by the operator.

#### c. Mechanical Configuration

The replacement of the two Itek absolute position detector units by the laser interferometer necessitates the addition of two PC cards for the stages' absolute position up/down counters and two PC cards for typewriter control.

The increased range to seven digits requires the addition of two arithmetic unit PC cards. As a result, the capacity of the DSMS card rack system is exceeded and requires the addition of a second card rack.

Due to the additional 6 PC cards, the capacity of the DSMS +5 Vdc power supply is exceeded and required a larger unit (27.5A) versus the old 16A. (Under worst case conditions, the +5 Vdc power supply loading is calculated for 22.0 A maximum.)

In place of the two power supply assemblies that were used for the Itek metering system, a single power supply assembly is provided for the interferometer metering system.

The LFDSMS servo drive system circuit configuration is illustrated in Figure 1.



## SECTION III

### INTERFEROMETRIC METERING SYSTEM

#### a. Optical-Mechanical

The LFDSMS uses a Hewlett Packard Model 5501A laser transducer as the basis for a plane mirror interferometer linear displacement measuring system. The system performs measurements to a resolution of 0.1 micron over the area of the two mensuration stages.

The configuration, as shown in Figure 2, consists of a one-piece mirror with two orthogonal plane surfaces. The two axes of measurements for each stage are closely co-planar with the film stage platen and intersect at the microscope objective optical axis. This configuration minimizes errors that result from mensuration stage pitch and yaw.

The one-piece two-axis mirror is secured to the XY stage through a three-contact mount that allows for thermal expansion of the stage without losing alignment and minimizes zero reference drift. The interferometers are rigidly coupled to the exterior support structure. The mounting of the balance of the interferometer components is not as critical.

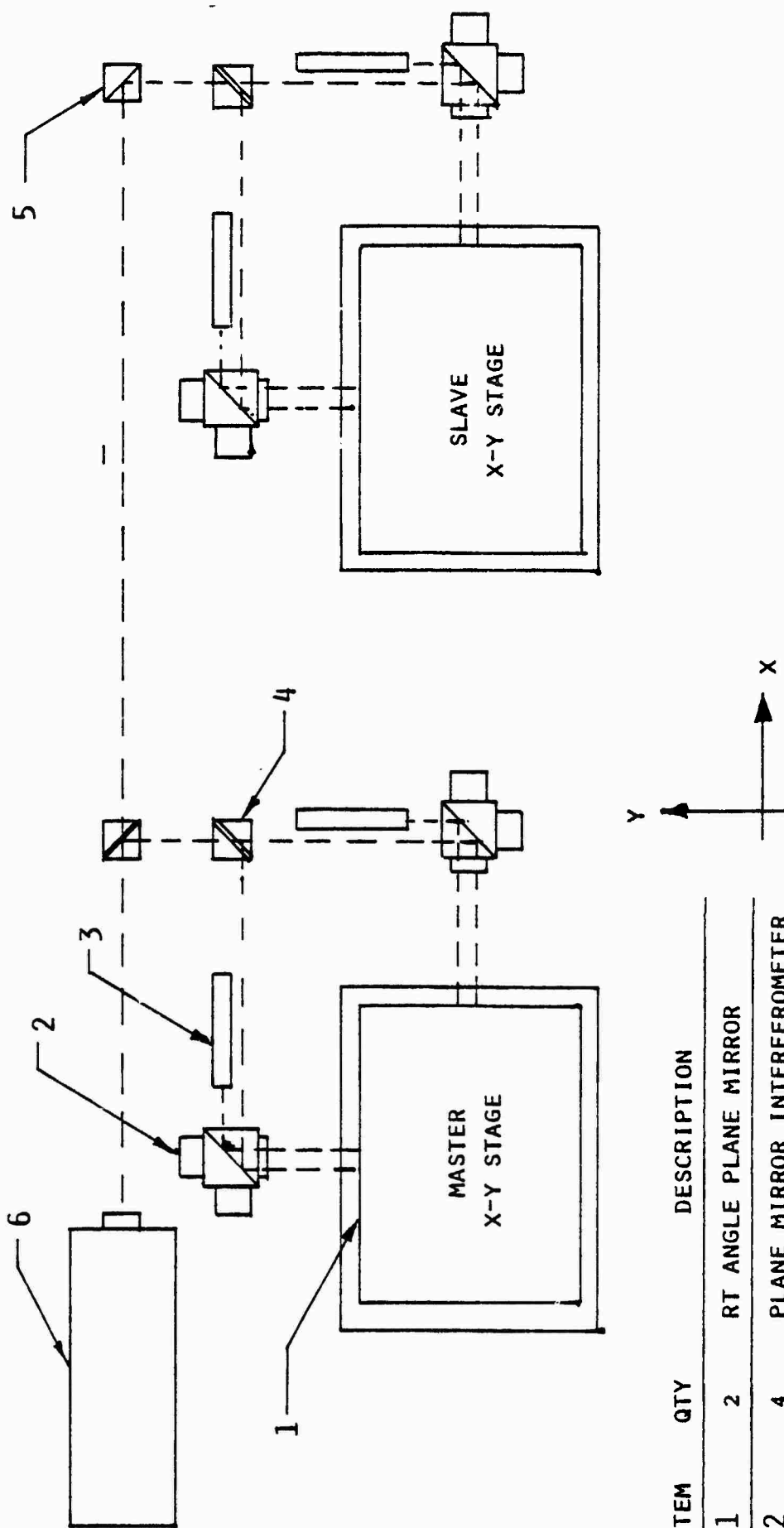
An enclosure over the fixed portion of the laser path is incorporated in the design. Because of the X-Y motion of the stage and the need for film accessibility, shielding of the variable portion of the laser path was not provided.

#### b. Performance

The Hewlett Packard Laser Measurement System has a basic accuracy of  $\pm 5$  parts in  $10^7$  [ $\pm 0.15$  micron in 300 millimeters (12")  $\pm 2$  counts]. This assumes a perfectly stable air temperature, pressure and humidity. Since actual measurement environments are not perfectly stable, correction is required when the environment deviates from nominal values. This is done manually via thumbwheel switches on the front panel of the metering electronic card rack.

In order to attain best accuracy in measurements, the operator must monitor the parameters that are critical and make adjustments of the thumbwheel switches as required. As an example of effects on air density, an error of approximately one part per million results for a change in air temperature of  $1^\circ\text{C}$ .; or 2.5 mm. Hg. barometric pressure change; or a 30% change in relative humidity.

In addition to the above errors, major contributors to



ITEM	QTY	DESCRIPTION
1	2	RT ANGLE PLANE MIRROR
2	4	PLANE MIRROR INTERFEROMETER NO. 10706A
3	4	RECEIVER NO. 10780A
4	3	50% BEAM SPLITTER NO. 10701A
5	1	BEAM BENDER NO. 10707A
6	1	LASER TRANSDUCER NO. 5501A

LFDSMS METERING SYSTEM

FIGURE 2.



inaccuracy are non-flatness of the plane mirrors on the moving stage, non-orthogonality of the laser beam (cosine error) and non-orthogonality of the two plane mirrors. Non-flatness of the mirrors is a direct error and is a maximum of  $+ 0.32 (\lambda/2)$  microns. Non-orthogonality of the two plane mirrors results in errors proportional to the measured distance and does not exceed 5 parts per million. Non-orthogonality of the laser beam is controlled to result in a maximum error of less than 0.1 parts per million. Thermal expansion effects are potentially the largest source of error. Over a short time interval, thermal inertia of the stages and critical supporting structures holds the error to a very small magnitude. Over long time periods, while the temperature is changing, thermal expansion can result in significant errors unless the stages are reset at the 0-0 position.

Thermally active materials such as aluminum are used in non-critical applications or as temperature expansion compensating elements. Temperature effects are minimized by designing with materials that have nearly matching thermal expansion coefficients and by adhering to semi-kinematic mounting methods. It is evident that film input is very active with respect to dimensional changes occurring when temperature changes, as well as when moisture content changes. Polyester film (DuPont Mylar) base has a reported thermal expansion coefficient of 30 ppm per °F and 6 ppm per % relative humidity. The values are also different in different directions, showing as much as a 2 to 1 variation. This sensitivity can result in a possible error of approximately  $0.7 \mu\text{M}$  in 20 mm when the temperature and relative humidity changed by 1°F and 1% respectively.

### c. Results

A serious problem surfaced during the final alignment and T & A period. It was found that the metering system suffered from occasional (at times, frequent) miscounts or dropouts. It soon became apparent that air temperature gradients in the interferometer beam was the cause. The stage illumination assembly proved to be one source and required the addition of a liquid cooling system. By shielding the LFDSMS from cold or hot drafts, it was found that the dropout rate decreased to a low value and was not a serious problem.

## SECTION IV

### OPTICAL SYSTEM

The LFDSMS optical arrangement is similar to that of the DSMS and utilizes many of the same optical elements. Primary differences were dictated by the increased distance between the master and slave stage optical axis. A wood mock-up was evaluated at FTD by many of the personnel that have been working with the Micron Stages and the DSMS.

It was agreed that the following modifications would be incorporated in the final design, if possible:

- a. Readout switch and stage lock switch to be relocated near the left hand control knob.
- b. The interferometer zeroing gages would require modification for easy reading.
- c. Stage positioning controls should be relocated, if possible, for easier control (same elevation, clearance).
- d. Reset controls should be protected from accidental actuation.
- e. Eyepieces should be inclined so that operator is looking down.
- f. Several mechanical changes that would improve the maintainability and reduce the possibility of damage.
- g. A lower magnification with large area viewing is desired.

As the final design progressed, most of the desired changes were implemented in a second mock-up that was again evaluated at FTD in December of 1976. This mock-up was well received, with only a few modifications requested. Results are as follows:

- a. The master stage lock switch is not required near the left hand control.
- b. Metering re-zeroing switches are to be one for each stage and protected.
- c. The console vertical height adjustment is reduced to + 4 inches.
- d. An audible alarm is to be provided for miscount or beam

interrupt.

- e. Easier focus and reticle rotation controls are to be provided on the slave stage.

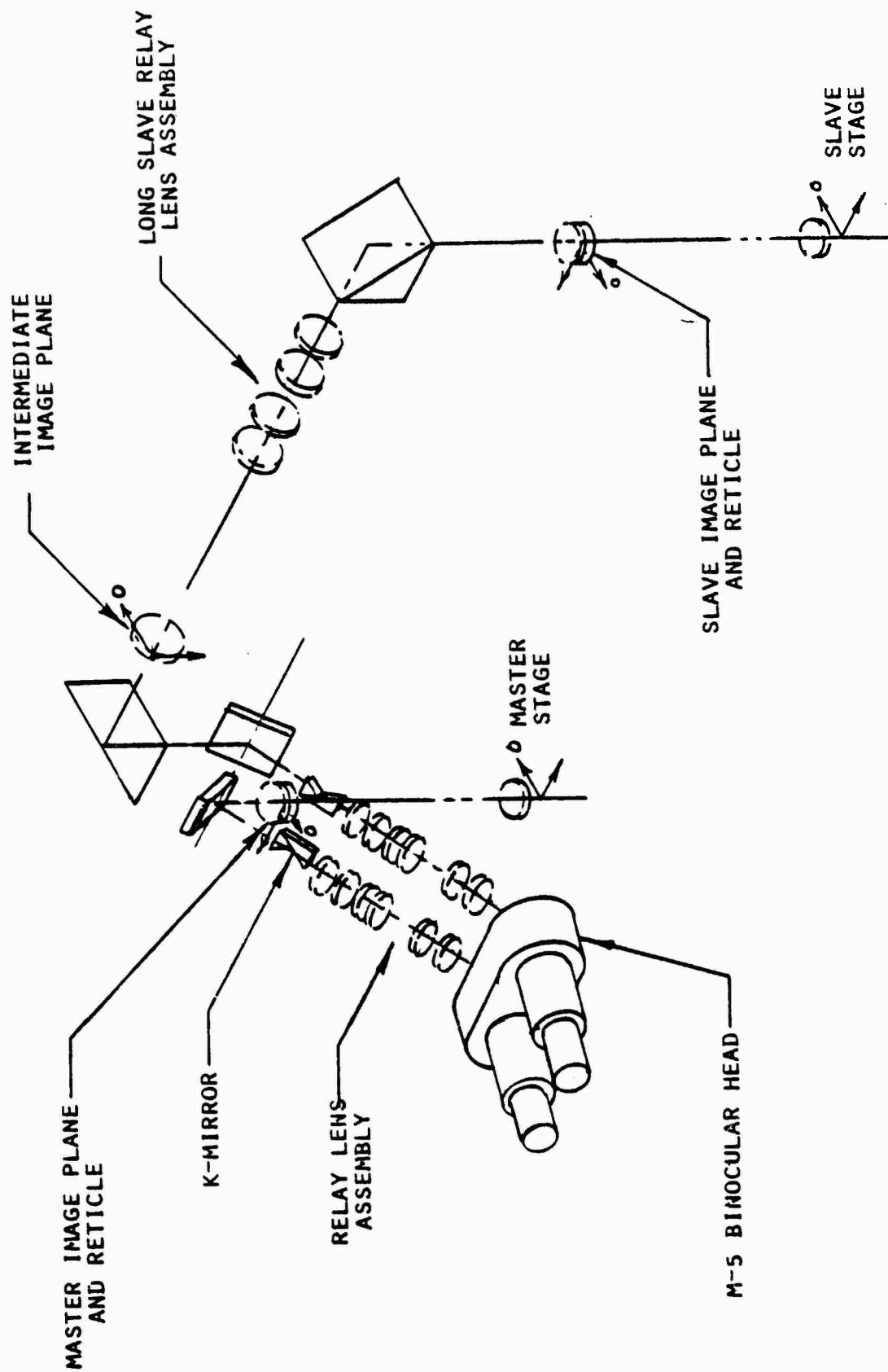
The optical arrangement, as shown in Figure 3, uses focus-microscope objectives at each stage with a fixed reticle rigidly attached to each stage base. This allowed flexibility of movement between the two stages without changing each table's reference. It also relaxes mechanical requirements on the rigidity of the structure supporting the tables.

The final detail design of the LFDSMS optics was controlled by the focusing microscope, microscope objectives, and the binocular eyepiece head. The location of the reticle with respect to the platen was restricted by the travel of the focusing microscope. A normal microscope has the reticle attached to the eyepiece, operates at a fixed magnification, and focusing is accomplished by moving the objective and reticle with respect to the object. In the LFDSMS design, there is a fixed object and image (reticle) plane. Focusing is accomplished by moving the objective between the object and the reticle (image plane) allowing magnification to change. With an 8.20 inch track, the magnifications for the objectives ranged from 1.6X to 23X and resulted in minimum refocusing when changing objectives. In order to optimize the diameter of the crossover tube, the system f/number was set at f/18, for each relay. This is a significantly smaller f/number than any of the objective exit f/numbers and, therefore, maintains high resolution for the overall system.

The three relays lenses were each designed as two objectives for unit magnification. The two eyepiece relays have a length controlled by the optical path length through the binocular eyepiece and the mirror clearance. Other considerations were the angle of the eyepiece assembly and position of the eyepieces with respect to the edge of the table.

The master stage eyepiece relay was designed in two parts with collimated light between. The part nearest the eyepieces is called the common eye lens and is common to both the master and slave relays. The common eye lens design then dictated the overall length of the slave eyepiece relay. The second slave relay lens located in the crossover tube was then designed to fit between the slave reticle and the intermediate image plane.

Field lenses were inserted where required and were designed as part of the optical system. A field lens is used to prevent vignetting while directing light from an intermediate image into the next lens of the relay system. There are three field lenses in this system. One, in the master stage optical system, directs images from the microscope aperture into the eyepiece relay. There are two field lenses in the slave stage optical



OPTICAL SCHEMATIC DIAGRAM

FIGURE 3.

system; one to image the aperture of the microscope objective into the slave relay lens in the crossover tube, and the second to image the aperture of this same slave relay into the aperture of the slave eyepiece relay.

The configuration of the relay lenses and mirrors were arranged to give the slave image to the master image identical orientation. This image still had a right-to-left reversion as compared to the M5. Solid "K" mirrors provide odd number of reflections. By properly orienting the reflecting surfaces, a reversion was obtained without affecting the vertical orientation of the image.

## SECTION V

### MECHANICAL SYSTEM

#### a. Stage Design

The initial approach, in keeping with the intent of the Statement of Work (S.O.W.) was to enlarge the stages that were used in the DSMS system so that measurements could be made over a 200 mm by 300 mm area. It soon became apparent that this approach was unacceptable for several reasons. First, the overall size of the system would grow to prevent compliance with the 38-inch doorway requirement. Second, the increased depth of the combined base structure and measuring stages would nearly eliminate leg clearance. Third, the distance from the operator position to the slave stage optical axis would make it impossible for the operator to adjust a small film chip while observing it through the eyepiece. Fourth, to keep the weight within S.O.W. limits would dictate the use of aluminum construction and result in excessive drift from thermal effects. Fifth, the multi-groove gas bearing design of the DSMS would be extremely difficult to extend without increasing the bearing clearance significantly. The larger clearances would then result in much softer bearings (lower spring rate) and cause severe servo positioning problems.

The foregoing reasons demanded a completely different design that would meet the requirements of the S.O.W. Since present day techniques can easily produce granite parts in the accuracy and sizes required, and since granite has many desirable characteristics, the decision was made to proceed with granite in the design of gas bearing guides and the flat bases. Granite was also used for other structures that required matching thermal expansion coefficients.

#### b. Frame

Attempts to find a commercially available support frame with all the features required (adjustable height, lockable wheels, easily moved, and adequate knee clearance) were not successful. The task of designing the frame structure was then undertaken in parallel with the design of the stages and the optics.

The support frame in the LFDSMS has several extraordinary requirements, compared with those of the DSMS. First, the combined weight of the stages is nearly 1000 lbs. (Each granite base measures 24 x 28 x 4 1/2 inches and weighs about 300 lbs.) Second, the system has 10 times the digital resolution, making it much more susceptible to jitter and roll of the output. Third, the metering system is not autonomous for each axis, as

in the DSMS. The integrity of the alignment of the laser optics path through four interferometer axes dictates that the two granite plates remain coplanar within a small fraction of an inch.

The above requirements lead to a design that embodied a four-legged, somewhat flexible, subframe supporting the main frame at three points by means of coupled parallel drive jack-screws. The main frame, by virtue of the design, is nearly free from torsional deflection due to an uneven floor that imparts twist in the subframe. Each screw is also individually adjustable so that unevenness of the floor can be eliminated in its effect on non-levelness of the stages and the resulting gravitational biasing of the servo drive. The main frame, in turn, supports the two stage bases in three-point semi-kinematic mounts. Lateral restraint of the bases is provided by spring loading against adjustable stops. The stage bases also mount the interferometer components as well as the viewing optics support structure, thereby establishing maximum integrity between these critical elements.

The operator control panel, as shown in Figure 4, has been rearranged from the DSMS panel to provide the metering reset switches and places the controls in more suitable locations. The operator can rest the heel of his hand on the panel while using the joystick, without inadvertent actuation of other controls.

### c. Moving Stages

A basic rearrangement from the DSMS was necessary with respect to the location of the control knobs on the master stage and the servo drive motors on the slave stage. The control knob and the servo motors on the LFDSMS are both attached to the intermediate stage and therefore maintain a fixed relationship to each other. The motion of the intermediate stage is constrained to the X-direction (left to right with respect to the operator) so that the operator only moves his hand in unison when fine positioning the master stage, using the control knobs. With the DSMS, the servo motor and left hand control knob (Y-Axis) was attached to the fixed base while the servo motor or the right hand control knob was attached to the intermediate stage (moves in Y direction). This requires the operator to follow the Y-motion with his right arm while his left arm is stationary.

Adjacent to the left hand control knob of the master stage is located the read-out switch. A very light touch is required to actuate this switch in order to minimize stage movement due to switch actuation. The switch is so positioned that the operator should not inadvertently activate the switch while adjusting the stage position. At the same time, he does not





have to move his hand from the knob to activate the switch.

The moving stage design employs granite parallels and gas bearings for lateral control of straightness of travel. Two parallel surfaces per stage are used in the LFDSMS whereas six parallel surfaces were used in the DSMS. Both the main stages and the intermediate stages are vertically supported on gas bearings (4 each) that, as in the DSMS, are in turn supported by the base plates. The main stages provide the mounting of the fluorescent collimated light source and the fused silica platen for support of film. The platen also provides the long plane mirrors that are the moving reflectors for the interferometer system.

Since it is necessary to have a zero reference device for the interferometer metering system, flat hardened steel surfaces were incorporated in the main stage and set closely parallel to the platen mirrors. Closely coupled to the plane mirror interferometers (passive component) are spring loaded plungers. The spring load is greater than the maximum drive force of the Roh'lix and insures a fixed position of the plunger except under impact. By using proper technique when setting the stages to the zero-zero position, the requirement for repeatability of  $\pm 1$  micron is easily met. Backing up the zero stop spring plunger are additional heavy duty spring plungers that prevent damage when the stages are moved too rapidly into the zero-zero position. The back-up spring plungers are in a different location from the zero set spring plungers and act very closely through the c.g. of each stage. This reduces the possibility of violent stage yaw and subsequent damage to the lateral gas bearings and guides. Additional heavy duty spring plungers are provided to prevent damage when the stages are moved to the opposite extremes of travel.

It would be possible to set up the zero reference steel surfaces very closely parallel to the reference mirror so that each axis could be reset to zero, independently. It was decided that, functionally, it is better to re-zero both axes simultaneously (single reset switch for both axes) thereby reducing the setting accuracy requirements of the steel surface.

Other methods of providing a zero reference position, considered early in the program, such as an LVDT (Linear Variable Differential Transformer) and dial indicators were discarded for various reasons such as reliability and difficulty of observation. The LVDT method seemed very attractive at first, since it could be designed to zero reset automatically when the operator moved the stage through the zero position. It was feared, however, that thermal drift might be excessive, along with reduced reliability as compared to the spring loaded plunger.

#### d. Optical System Mechanical Components

The LFDSMS optical/mechanical arrangement required considerable redesign of components that were used in the DSMS, as well as the addition of new ones. Minimizing thermal drift and providing easier access to adjustments also demanded changes from the DSMS design.

The most critical area in prevention of drift is in the mounting of the reticle and the microscope objectives. It can be appreciated that a point on the platen should remain aligned with the optical axis of the reticle and objective, even at different temperatures, when the metering system readout is unchanged. Since the different components involved have different thermal expansion, inertias, reflectivities, conductivities, and are actually exposed to different temperatures under changing conditions, exact thermal expansion compensation is not possible. The respective mounting components are therefore selected for thermal expansion coefficients and finishes and are arranged to provide minimum drift for temperature changes that affect all components equally.

The microscope objective holder and reticle are mounted in a single assembly (one for Master and one for Slave) that, in turn, is attached to the granite arbor. The granite arbor is cantilevered from a semi-steel casting which is attached to the granite base. These components were also designed for maximum rigidity so that vibration would not degrade imagery. The microscope slide is also positioned with the focus adjustment knobs on the operator side to give easier access than would be the case if the slide were positioned as in the DSMS. Since the Slave optical center line in the LFDSMS is farther away from the operator than in the DSMS, extensions were added for ease of focus plus reticle rotation.

The reticle holder was also redesigned to provide a five point, semi-kinematic, mounting. It is constrained in all degrees of freedom except for rotation about the optical axis. Reticle centering is adjusted at final assembly and should not require readjustment during normal use. The four fine adjusting screws can be accessed through the side holes in the reticle support ring if recentering is ever required.

The balance of the optical elements are supported from two similar housings that are attached to the top of the granite arbor. A cross-over connecting tube protects the relay lenses from contamination and has a slip joint to allow relative movements due to thermal expansion.

## SECTION VI

### PNEUMATICS SYSTEM

Early in the program, an investigation was undertaken to determine the best type of gas bearings to use in the LFDSMS. Granite will be the guiding surface; and, since the moving stages have increased in weight over the DSMS, analysis and experimentation were necessary.

#### a. Operating Criteria

Layout of the stages for the LFDSMS was undertaken on the assumption that, drawing from either of two families of air bearings (cavity vs. simple drilled hole), we could deliver a load of about 12 pounds and a stiffness of at least one pound per micron of deflection, in a pad area of one square inch.

The layout evolved a design with 24 bearing orifices or "pads" in each of the two 8" x 12" X-Y subsystems. For comparison, the 4 x 4 inch DSMS required 32 cells in each subsystem and the moving mass was only 40 percent as great.

The bearing complement in the LFDSMS is as follows:

#### Guide Bearings

X Stage	8
Main Stage	8

#### Support Bearings

X Stage	4
Main Stage	<u>4</u>
Subtotal	24
x 2 =	48

Granite elements resembling commercial "parallels" were selected for the Guide Ways. The guide bearings are disposed in rigid "Yokes" in which two bearing pads, having an area of a square inch, are housed on each of two hardened stainless "Gib Plates". The two pads were merged into an elongated octagon, so that the total area was 2.2 square inches. The Gib Plates are separated by a granite element which was matched to the Way in sections. Bearing gap is preset by a single shim in the clamped Gib Yoke Assembly.

A third air bearing performance criterion was identified for the guide bearings. This was "bottoming resistance". It was recognized that in manual positioning, the stages which have an estimated combined weight of 85 lbs. could develop significant kinetic energy. The snubbing system now proposed

provides a two-stage spring-type kinetic snubber in which energy from minor abuse requires a maximum decelerating force of one "g".

The snubbing elements are disposed so that, in a "kinetic stop" the ways sustain the decelerating force from only one of the two stages, in each axis of travel. Worst case is a kinetic stop in the Y direction, in which the Main Stage, weighing about 50 lbs., is stopped by the X stage. Thus, the X ways sustain approximately 50 lbs. of transverse loading for a one-g stop.

The operating load of an individual bearing pad serves only to deflect the yoke which supports it. As the bearing gap "h" is reduced by an external force, the reaction load increases to some value that is about 1.4 to 1.5 times the operating load, at  $h = 0$ . The gap in the opposite bearing increases to  $2h$ , and its reaction load is reduced. The difference of the two loads "B" is the "bottoming differential". Numerically, it is roughly equal to the operating load for a single pad, but two opposed pads are required to deliver it. Because each individual way system comprises four opposed pad pairs, the "B" value for the pads should be 12.5 lbs., if the ways are to sustain 50 lbs. of load before hitting bottom.

The granite-to-hardened stainless interface is highly wear resistant, but scuffing and bottoming should obviously be kept to a minimum.

The support pads or risers have only to carry loads, providing only moderate stiffness. It is desirable to keep their diameter small to conserve layout space and to forgive out-of-parallelism with the base plane. Their load carrying capacity per square inch should be at least 10 pounds. Absolute load per pad must be tailored.

Another operating criterion for the LFDSMS is that the air supply system be autonomous for each machine. Air supplies for the earlier systems had to be enclosed in a soundproof box, despite the fact that they were low-performance, low-noise systems in the first place. Supply pressures were limited to 25 psig and total flow was less than one scfm per stage. The sound level of the auxiliary cabinet was believed to be somewhat objectionable to the customer, although there is reason to believe that the cooling fans, not the muffled compressor, were the principal sources of noise.

#### b. Initial Selection of an Air Bearing Type

Some consideration was given early to the use of the simple "drilled hole" type of air bearing because of its low cost, its inherent resistance to oscillation at all pressures and gaps, greater freedom from stoppages, and because some operating data

was already available.

The drilled hole or "simple" bearing is intrinsically less efficient than the cavity-and-orifice type bearing, at a given operating pressure. Literature indicates that cavity bearings are 1.5 to 2.25 times stiffer. The drilled hole bearings are expected to be capable of developing only about 15 to 20 percent of their supply pressure as an operating load.

No curves were available for the Link modular, cavity-type bearings used in earlier machines. However, it was expected that they could develop 50 percent of their supply pressure as an operating load, suggesting that the 12 pound criterion could be met with a quiet diaphragm pump, at 25 psig. It was assumed that even if this "pressure efficiency" was optimistic, the bearing parameters could be refined to permit operation at a higher pressure.

#### c. Cavity Bearing Tests

Initial tests were begun, and abandoned, using a fifteen-pad circular stator from the laser/scanner/recorder spindle. A 2.2 x 2.5 x .9 inch, four-cell test pad (Dwg. C11825) was designed to utilize the standard Orifice Insert (Link Dwg. 679960). This specimen was centrally loaded through a ball, from a simple (aluminum) beam on which calibrated weights were applied at a 2=1 mechanical advantage. The bearing surface was a moderately worn Standridge surface plate (California black granite).

The same pad was tested in four consecutive versions. The first three versions embodied two "coupled pairs" of pads in which the orifice pairs were located in two 2.2 x 1.14 inch elongated octagons, similar to the layout design of the gib plate. In the final modification, the pads were separated into four roughly symmetrical octagons simulating four 1 1/8 DIA (one-square-inch) circles.

Two Federal electronic indicators, operating at a 20 millionths least count, measured lift of the test pad at opposed corners. An F & P "float" meter measured flow.

The tests were begun with a relatively deep cavity, to induce oscillation. Tests were run at 15, 25 and 40 psig. At each cavity depth, an "envelope" of instability at low gaps and high pressures was expected. The vibration-free operating envelope should enlarge as cavity depth decreased.

The four configurations tested were:

<u>Version</u>	<u>Pad Configuration</u>	<u>Cavity Depth</u>
-1	Coupled Pair	.010 +.000 -.004
-2	Coupled Pair	.006 +.0008 -.0010
-3	Coupled Pair	.003 +.0008 -.0006
-5	Discrete Pad	(Same)

- 1 - Instability (vibration) was observed in all cavity bearing tests. Contrary to expectations, instability occurred at 0.0002 inch and above, rather than at low gaps.
- 2 - Varying cavity depth (down to .003 inch) did not materially affect instability. It should be noted that the orifice insert has a radial clearance volume that is approximately equal to the volume in a .005 deep x 3/8 diameter cavity.
- 3 - In the coupled-pad configuration, the intensity of the vibration was low enough to permit gap and flow data to be taken throughout the whole curve, at 15 and 25 psig. At 40 psig the data could be taken only at the bottoming end of the curve, well below the operating point.
- 4 - When the pads were decoupled into four discrete octagons, the vibration grew much more intense. Violent oscillation occurred at 25 psig and only the lower part of this curve could be quantized.
- 5 - Contrary to expectation, only about 30 percent of the pressure could be delivered as an operating load. This meant that at 25 psig (assuming the stability problem could be debugged) one cell of a coupled pair could deliver only about a 7.5 pound load.
- 6 - Operating gaps were typically about .0004 inch.

At this point, it became clear that the cavity-type bearing could be adapted to the LFDSMS only if a major effort were made to control instability, to the point that an operating pressure of 40 psig could be sustained without a trace of vibration.

The effort would be to (1) almost eliminate the cavity, (2) increase the pressure, and (3) possibly enlarge the hole. In increasing the pressure, we must acknowledge that we depart

from the diaphragm compressor and settle for the noiser piston-type pump. The higher pressure and bigger hole also call for more flow of free air.

d. Simple Bearing Tests

In trying to determine operating parameters for simple bearings, previous empirical data was used. All previous tests had been run on single 1 1/8 diameter pads, and it was concluded that an .018 diameter hole was apropos for granite. It was decided to go one drill-size downward on the LFDSMS, to conserve flow.

Test specimen (C11918) was made, similar to the "cavity" specimen, except that a #78 (.017  $\pm$  .0003 DIA) drilled hole replaced the orifice insert.

This model was tested in three geometric versions, using the same setup as was used on the cavity series:

	<u>Geometry</u>	<u>Curves</u>
C11918-1	Coupled Pads	Figure 5
C11918-2	Discrete Circles, 1.00 DIA	Figure 6
C11918-4	Discrete Circles, .85 DIA	Figure 7

Figures 5, 6, and 7 show the expected "S" shaped curves. Maximum stiffness occurs at the inflection, which is also a fairly linear region. The midpoint of this linear region tends to occur at about 70 percent of the "bottoming load" in all bearings tested. To compare various pressures and geometrics, it was established that the operating gap was at a load which was 75 percent of the bottoming load. This effectively biased the bearings performance in the direction of lower flow and lower gap (at the expense of some bottoming differential, "B").

Stiffness and load on round pads are strictly proportional to pad area. The "coupled pad" concept improved stiffness and load by an amount in excess of what would be expected from the 10 percent increase in area per cell.

In setting up the stages, a pressure adjustment is necessary to trim the lift in view of the real weight, or to compromise mismatched loads on the feet. Figure 8 shows a plot of gap and flow versus pressure, at a constant load. Though not exponential with pressure, flow varies as about the 2.2 power of gage pressure near the operating point. Pressure should not be set lower than 90 percent of optimum because the rapid fall-off

of flow and gap signals that the bearing is losing stiffness and is ready to collapse. A five psi (7 percent) increase in pressure would raise flow 16 percent, with no loss of stiffness.

e. Air Supply: Pressure

In selecting a top pressure for the system, the gib yokes will work comfortably at 75 psig. The risers should have as much pressure as we can deliver (allowing for some reserve) to conserve pad diameter.

In examining the necessity for a dryer, thermodynamics calculations indicate:

- 1 - There is no tendency for the expansion of the air in the regulator, or in the bearing itself, to condense moisture. Temperature drops are very small.
- 2 - For every 10 psig of regulation drop, pressure dew point is depressed about 3 degrees F.

The moisture problem, then, is that the air out of the compressor is always saturated and is also quite hot. Thus, unless the air is cooled before regulation, or takes a huge regulation drop, water will condense in the feed lines to the bearings.

By the following expedients, the air will be cooled to within a few degrees of ambient temperature at the feed lines and eliminate the need for a dryer by taking a modest (15 psi) regulation drop:

- 1 - Utilize the long hose from the cabinet to cool the air.
- 2 - Place the two tanks (2 gallon reservoirs) on the machine frame, remote from the warm pump and electronics.

Condensation will take place in the hose and tanks. All condensate will collect in the tanks where it is drained daily by the operator. The saturated air in the tanks will have some liquid-phase fog. To prevent this from entering the regulators (which are above the tank at the right side of the knee-hole), a Wilkerson Micronaught 0.3 micron filter is provided. This is the only other operator-maintained pneumatic component.

With a 15 psig minimum regulation drop (4.5 F. dew point suppression, approximately) and 90 psig as the highest "turn-on" pressure for the compressor's pressure switch, the maximum regulated air bearing pressure becomes 75 psig.

The LFDSMS has its regulators packaged with the stages.



Alternate supplies can be used interchangeably, provided they can deliver cool saturated air at 90 psig min. With the addition of a dryer, the system could run on wet 80 psig shop air.

f. Specific LFDSMS Bearing Design and Performance Parameters

1 - All Air Bearings:

Material: Type 440C - All machining, including holes, before hardening. Harden to Rc 55-60.  
Grind and lap face.  
De-Gauss.

2 - Guide Bearings:

Yoked, coupled pairs 1.1 x 2.2 inches.

$d = .017$  dia. (#78 drill)

$p = 75$  psig.

Total pads/system: 32

Gap, h:

Thereoretical: .00037

W (operating load) = 13.4#

B (Bottoming Differential) = 12.8 #/Pair  
= 51.2 #/Stage

k (Stiffness) = 1.33#/ $\mu$ /pad  
= 10.6#/ $\mu$ /stage

Q (Flow) = .036 scfm/pad  
= .144 scfm/yoke

Notes re gap:

a - Theoretical optimum gap may be 10 percent higher due to instrumentation error in tests.

b - Operation with lamp at maximum intensity may cause 30 to 40 millionths growth in "Y"-gap (only). Y-ways have reduced requirement for bottoming differential and may be safely operated at 25 to 50 millionths less gap (8 or 15 percent less flow) than the X ways, measured cold.

c - Gap is set by shimming one side of yoke with Mylar sheets which are nominally 2h thick.

### 3 - Riser Bearings:

#### Assumptions:

- a - Nominal Design Life Pressure will be 70 psig normal; variable from 60 to 75 psig by means of two regulators. One regulator controls both X-Stages; the other controls both Main Stages. The ability to raise the pressure 5 psi above the nominal gives a reserve factor of

$$\left(\frac{75}{70}\right)^{1.17} = 1.082$$

against miscalculation of stage weight.

- b - All pads will be round.

- c - Performance Parameters:

(Per 1 1/8 dia. pad)

	X Stage	Main Stage
d - Hole Diameter	.017 inch (#78 Drill)	.021 inch (#76 Drill)
Q - Flow	.036 scfm	.047 scfm
h - Optimum	.00043 inch	.00045 inch
W - Optimum Load	10.2#	10.6#
k - Stiffness	0.96#/u	0.92#/U

- d - Effect of varying pad size:

Q - negligible change

h - negligible change

D Pad Diameter	Area, inch <sup>2</sup> , Load Factor, Stiffness Factor
.875	.60
.937	.69

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<u>D</u> <u>Pad Diameter</u>	<u>Area, inch<sup>2</sup>,</u> <u>Load Factor,</u> <u>Stiffness Factor</u>
1.00	.78
1.06	.89
1.12	<u>1.00</u>
1.19	1.10
1.25	1.22
1.31	1.36
1.38	1.48

4 - Total System Flow:

Gibs:

$$32 \times .036 = 1.15 \text{ scfm}$$

X Risers:

$$8 \times .036 = .29$$

Main Risers:

$$8 \times .047 = \underline{.38}$$

$$\text{Total: } 1.82 \text{ scfm}$$

NOTE - 1. .017" DIA HOLES (4)  
 2. PADS - COUPLED PAIRS  
 3. Q = SCFM AIR FLOW

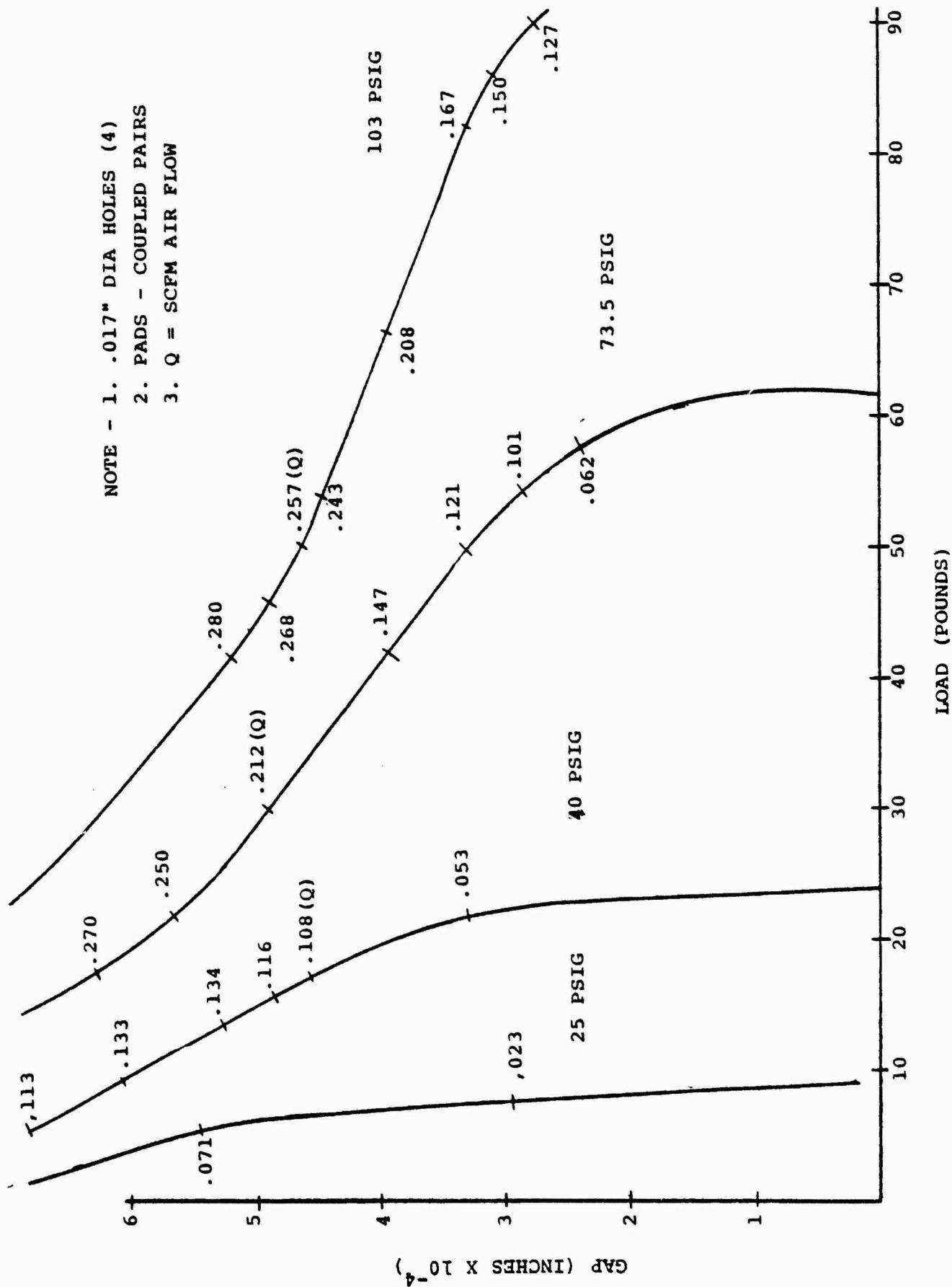


FIGURE 5. BEARING GAP VS. LOAD

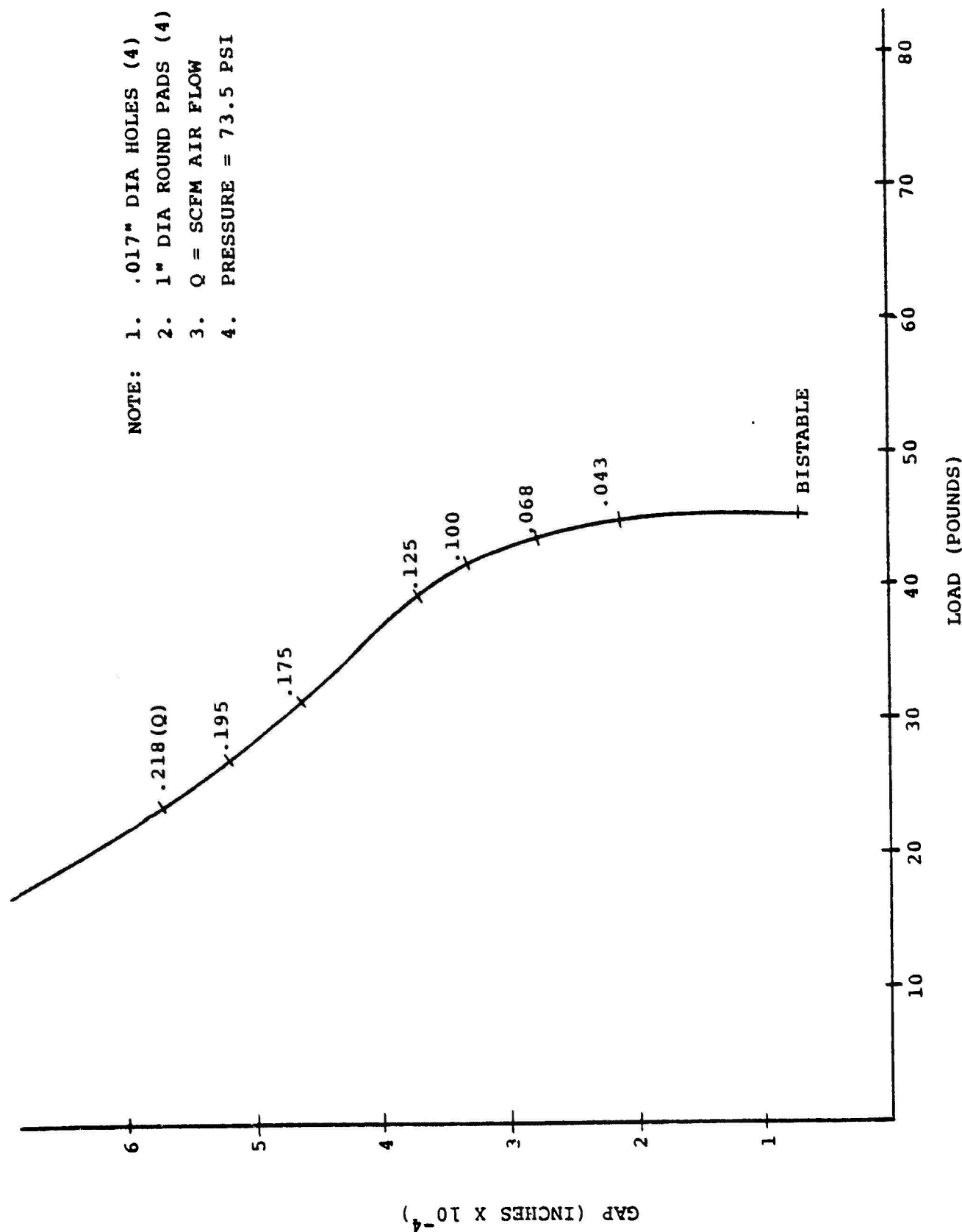


FIGURE 6. BEARING GAP VS. LOAD

- NOTE - 1. .017" DIA HOLES (4)  
 2. .850" DIA PADS (4)  
 3. Q = SCFM AIR FLOW  
 4. 73.5 PSIG & 103 PSIG

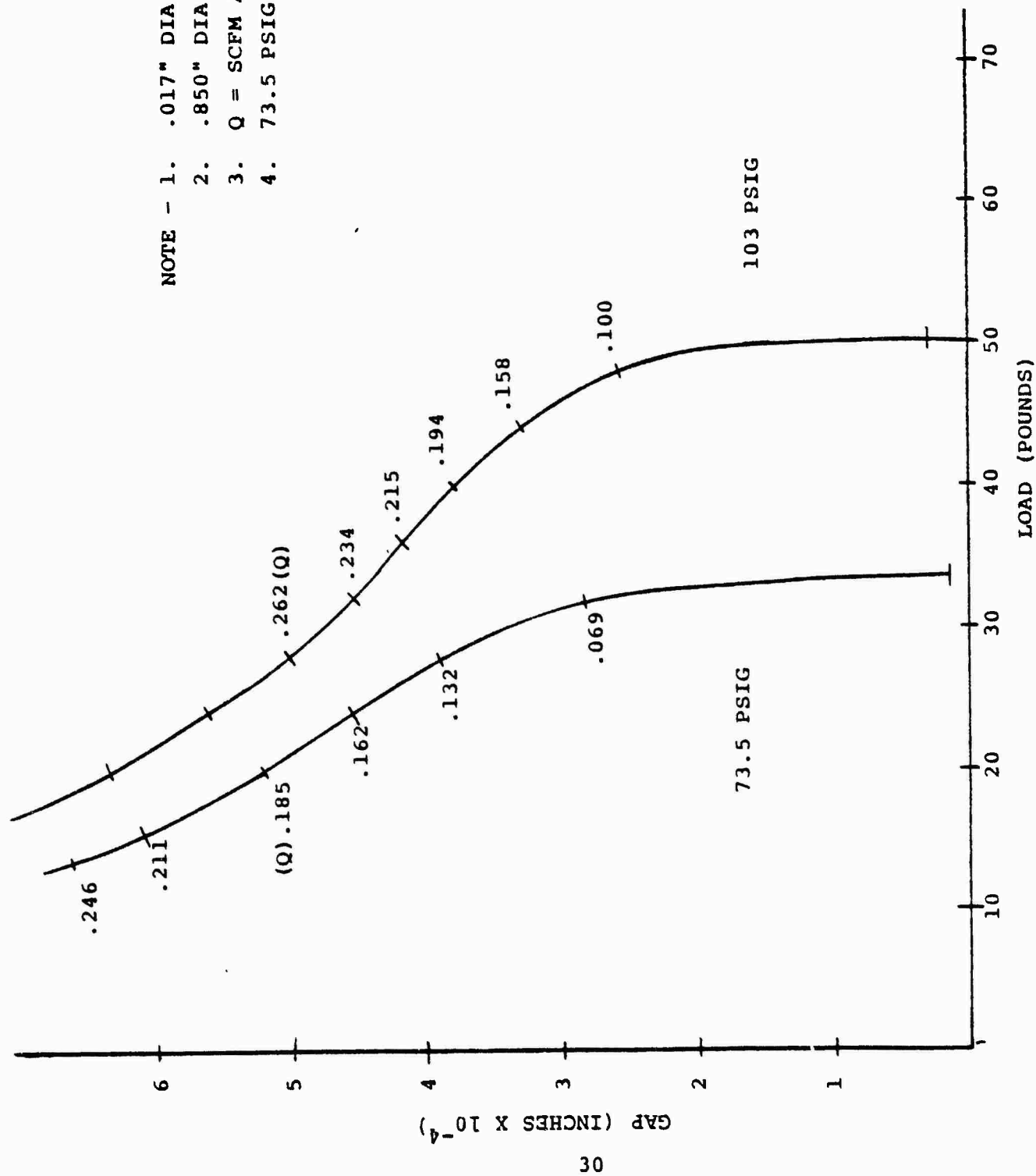


FIGURE 7. BEARING GAP VS. LOAD

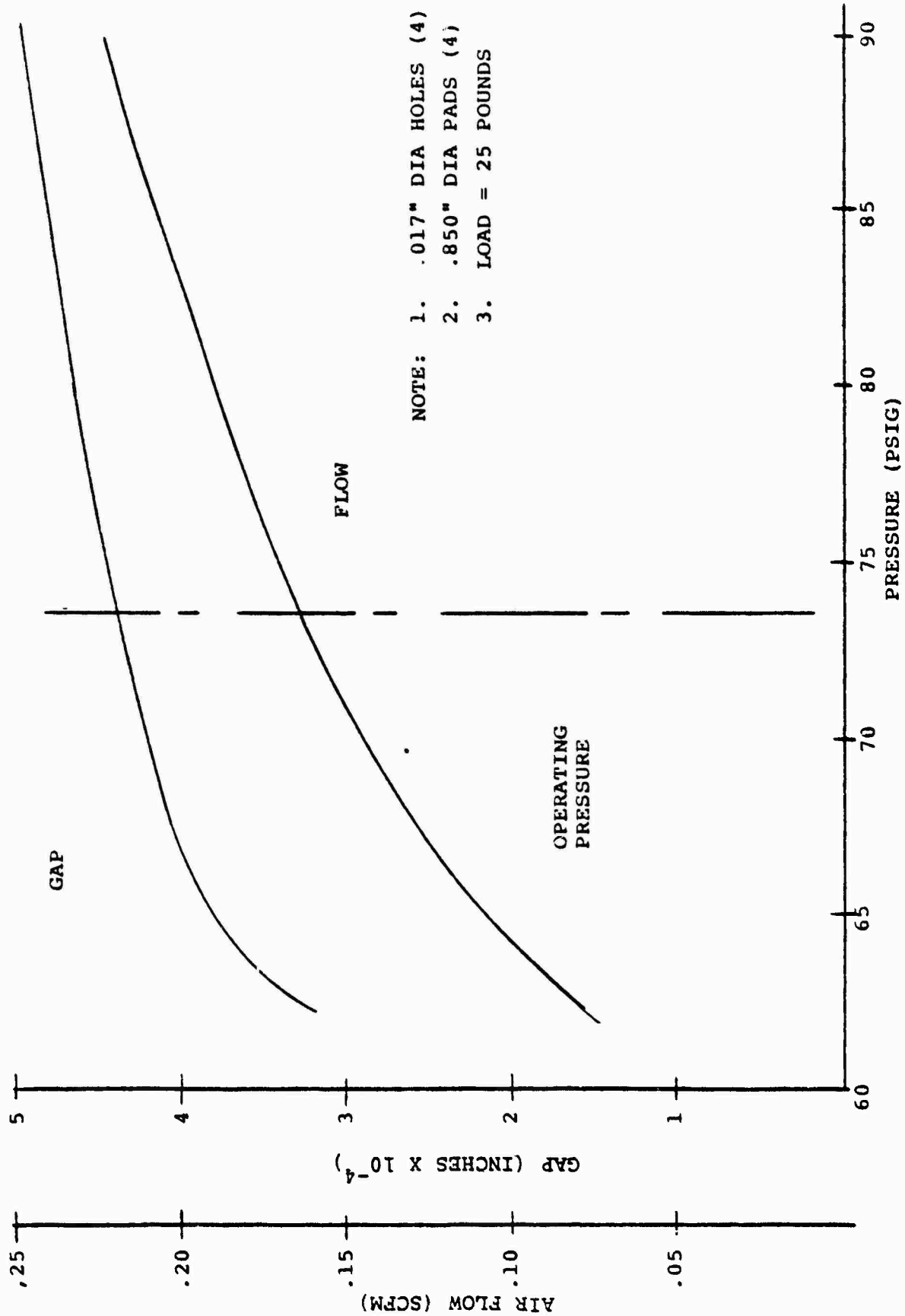


FIGURE 8. BEARING GAP & AIR FLOW VS. PRESSURE

## SECTION VII

### CONCLUSIONS AND RECOMMENDATIONS

#### a. Conclusions

The LFDSMS system is capable of extracting three-dimensional data from stereo film chips. The operator can quickly align the film chips to obtain a stereo model for mensuration. The accuracy and viewing/measuring area exceed those of the DSMS. The optics and servo system permit introduction of parallax for extracting three-dimensional data and the tracking of the slave stage to the master stage within  $\pm 0.2$  microns.

The physical arrangement provides comfortable viewing by an operator seated in a conventional office swivel chair with more than adequate knee clearance. The operator can also, while seated and looking in the eyepieces, adjust the console height to the most comfortable position. He can easily reach all necessary controls while looking in the eyepieces, as well as record coordinates without removing his hand from the master stage fine motion control knobs.

#### b. Recommendations

A larger field of view would be very desirable, particularly at the lower magnifications. This would require special low power objective lenses, a larger reticle blank, larger relay optics, and perhaps a different binocular microscope head and eyepieces. It is felt that the higher powers are not used as frequently as the low power and could perhaps be reduced in a future system.

A Hewlett-Packard (manufacturers of the laser metering system components) representative suggested that greater freedom from dropout would result if two 5501A laser transducers are used instead of one. The power would be increased by a factor of two, and the threshold could be set at a lower level than the present 40% to 50%.

When the LFDSMS was installed at FTD, it was found that the system was not suitable for use as a monosystem (master stage only) since the printout always included the slave stage coordinates. The programs available evidently cannot reject the slave stage coordinates when set up for mono work. It is inherent in the present LFDSMS system that both stages' coordinates are always transmitted when the readout switch is actuated. There was no requirement otherwise in the Statement of Work. It is felt that a modification of the system is feasible to eliminate this problem and it can be implemented at FTD.



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